CONF-800523--1

LA-UR-80-816

TITLE: FUEL-CELL-POWERED GOLF CART

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SUBMITTED TO: Third International Electric Vehicle Exposition and Conference, St. Louis, MO, May 1980

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Abstract

This paper describes the implementation of a battery/fuel-cell-powered golf cart test bed designed to verify computer simu ions and to gain operational experience with a fuel cell in a vehicular environment. A technically untrained driver can easily operate the golf cart because the motor and fuel cell controllers automatically sense and execute the appropriate on/off sequencing. A voltage imbalance circuit and a throttle compress circuit were developed that are directly applicable to electric vehicles in general.

Background

Because of its inherently high efficiency and low emissions, the fuel cell represents an appealing technology for application as an automotive power plant. Developments stemming from space, military, and utility applications have brought the technology to the level that fuel cells must be seriously considered for application in vehicles. Other assets of the fuel cell are that it is not dependent upon petroleum-derived fuels for its source of energy, it can carry sufficient fuel (energy) on board to provide long-range operation similar to today's internal-combustion-engine vehicle. Also, its efficiency does not decrease at low loads.

A recent paper (IECEC, August 1979) has described the results of a detailed economic study in which several vehicular applications for fuel cells were evaluated. Another paper (SAE, February 1980) has described the systems' considerations in properly sizing and matching the fuel cell and other components to the vehicle. A system configuration found very promising in these papers is a fuel cell in parallel with batteries. The batteries will meet peak power requirements and the fuel cell will provide cruise power and recharge the batteries.

This paper will describe the actual implementation of a battery/fuel-cell-powered golf cart. Emphasis will be on hardware and the actual subsystem design of an operational system.

Purpose

The golf cart shown in Figure 1 is primarily a test bed, designed to contribute to the verification of LASL's vehicle simulation program and to gain operational experience with the fuel cell in a vehicular environment. A golf cart was selected as the mobile test bed because of the availability of an existing fuel cell stack designed and developed for the Electrochemical Division of the Army's Mobility Equipment Research and Development Command (MERADCOM) at Ft. Belvoir, Virginia

No fuel cell is currently available that was specifically designed for a vehicular application.

The golf cart will help provide the experience necessary to develop and evaluate subsystems for the fuel cell peculiar to vehicle application and will provide base-line data to better define what attributes a first-generation vehicular fuel cell should have.

The Fuel Cell

The fuel cell installed in the golf cart is an air-cooled, 80-cell, 2-kW, phosphoric acid unit purchased from Energy Research Corporation (ERC). This fuel cell is a copy of a light-weight energy plant developed for the Army for portable power generation with no special emphasis given to potential vehicular applications. However, it is representative of the current level of development of phosphoric acid fuel cell technology.

The phosphoric acid fuel cell is technologically more advanced than the other types of fuel cells (solid electrolyte, alkaline, molten carbonate, solid polymer electrolyte) as a result of Department of Energy (DOE) and Electric Power Research Institute (EPRI) emphasis on utility power generation and MERADCOM's portable power plant programs during the past few years. Also, the operating temperature range of 150° to 200° C in this system is comparable to the range required by a steamed methanol reformer (a device for converting methyl alcohol to hydrogen, to be more fully discussed in the last section), thus allowing for the eventual utilization of thermal feedback techniques to increase system efficiency.

Stack Construction

The mechanical construction of the phosphoric acid fuel cell is relatively simple and is therefore amenable to mass production. Figure 2 shows a nominal 48-V stack assembly similar to that used on the golf cart. It consists of 80 cells. Each cell in turn consists of three key components -- the electrodes, the matrix, and the bipolar plates. Figure 3 shows the components for a 2" x 2" cell assembly to illustrate the assembly. The electrodes (not shown) consist of a thin layer of catalyst laminated to a thin high-porosity graphite paper impregnated with teflon to reduce wetting. The anode (hydrogen electrode) is impregnated with approximately 0.25 g/ft^2 of platinum catalyst and the cathode (oxygen electrode) is impregnated with approximately 0.5 g/ft^2 for a total platinum loading of approximately 0.75 g/ft^2 per cell. At these loadings the cell current density is 100 A/ft^2 at 0.6 V for a nominal power density of 60 W/ft^2. The 5" x 15" electrodes in the 2-kW stack have an effective area of 0.4 ft^2 for a nominal current density of 40 A/ft^2. Figure 4 shows a polarization curve (voltage vs current) for the 2-kW fuel cell stack.

The phenolic resin matrix is sandwiched between the two electrodes and "holds" the phosphoric acid electrolyte similar to a blotter. Notice that the acid is not contained in a reservoir and thus is not going to slosh around or run all over everything in an accident.

The compression-molded bipolar plates are formed from a mixture of graphite (for good conductivity) and thermosetting resin powder. The plates are grooved to provide channels for directing the fuel and air flow. They are placed adjacent to the anode and cathode with the grooves at right angles to each other. The air bipolar plates are normally oriented such that the flow is across the smaller dimension of the stack to minimize the pressure drop to enhance air flow for cooling and oxygen supply. Note that the carbon plates are conductive and therefore provide the path for interconnecting the individual cells in series from positive to negative electrode. The stack voltage is therefore the summation of the individual cells. The stack is assembled with a dry matrix between the anode and cathode, which is later wicked with phosphoric acid. Current collectors with terminals are added at each end of the stack to provide a means for externally connecting a load. Figure 5 shows the basic stack assembly after it is fitted with the gas manifolding. Resistive heaters are placed adjacent to the stack assembly to provide a means for externally heating a cold stack up to operating temperature before a load is connected. Finally, the entire assembly is wrapped in insulation.

Configuration

The golf cart configuration shown in Figure 6 has all of the major propulsion components that a full-sized vehicle might have with the exception that it does not have a transmission. Our computer simulations, however, indicate that a propulsion system and drive train designed specifically for an electric vehicle may benefit in performance without the weight penalty of the standard transmission. A light-weight, two-speed transmission designed for metropolitan and highway driving may also be better than a heavier four-speed transmission.

The golf cart's 2-kW fuel cell can be fueled by either reformed methanol (refer to last section for a more detailed discussion of reformers) or hydrogen; currently hydrogen is used and is stored in aluminum scuba tanks mounted on the rear of the vehicle. The batteries are four 12-V SGL 27 deep-cycle traction batteries. These batteries, which total 4 kWh (20-h rate), allow separate testing in the all-battery mode. They may be charged via an external charger when operating in this mode.

The fuel cell and batteries are coupled together through a diode, which prevents the battery from forcing current through the fuel cell in the reverse direction. The fuel cell/battery parallel combination will share the load current in a natural fashion according to their individual polarization curves. The 2-kW fuel cell polarization curve shown in Figure 4 is again shown in Figure 7 superimposed over a set of polarization curves plotted from data taken on the golf cart's traction batteries for 100%, 50%, and 25% state of charge. It can be seen that for no motor load current demand, the fuel cell voltage is greater than the battery voltage. Thus, the fuel cell will charge the batteries, if necessary, and supply auxiliary load current. As the motor load increases, the lower impedance batteries will cause the batteries to begin to contribute an increasingly higher proportion of current to the load. The dynamics of this automatic load sharing will, of course, depend upon the battery pack's capacity and state of charge. However, with careful design, this approach appears to be a simple and effective means to accomplish load sharing.

The motor is a 4-hp General Electric series-wound dc motor. This particular fuel cell, battery, and motor combination is capable of peak power outputs over 15 hp. This motor is larger than the normal golf cart motor and was used so that the fuel cell/battery power source can be stressed (through the use of load sleds, if necessary). The original resistive controller that came with the golf cart was replaced by a Sevcon chopper controller large enough to supply power to a full-sized car. This controller has an adjustable current limit up to an average of 300 A, an adjustable acceleration response, and the logic for qualifying bypass (disconnecting the chopper and connecting the motor directly across the power source). Bypass is enabled approximately one second after the throttle is fully depressed and when the chopper duty cycle reaches approximately 80%. A safety feature, which causes the forward and reverse relays to open, thus disconnecting power to the motor if the bypass relay doesn't open when the throttle is backed off from full throttle, is built into the bypass logic.

Fuel Cell Control

The three main objectives of the fuel cell control system shown in Figure 8 are to meter the hydrogen flow to the stack as a function of stack output current, to minimize operator interactions for fuel cell start up, and to automatically shut down the fuel cell when it is turned off. There is a twofold purpose to minimizing operator interaction. The first is to demonstrate that a fuel cell vehicle can be simple to drive. The second is to minimize the potential for human error and perhaps irreparable damage to the fuel cell.

Fuel Flow Control

The amount of hydrogen required by the fuel cell stack is directly proportional to the stack's output current. It is appropriate, then, to meter the hydrogen flow rate to the stack as proportional to its output current. This demand type of control system is implemented in the golf cart by measuring the fuel cell current through a shunt in the negative lead. The voltage drop measured across the shunt is converted to an octally encoded digital signal that controls one or more of three solenoid actuated valves connected in parallel. Each valve is uniquely calibrated to allow a flow rate of hydrogen corresponding to 10, 20, or 40 A of stack output current. Thus, the "10-A solenoid" turns on for load currents up to 10 A, the "20-A solenoid" turns on for load currents between 10 and 20 A, and both the "10- and 20-A" solenoids turn on for load currents between 20 and 30 A, etc. To provide for additional cooling at higher load currents, an auxiliary fan located in front of the air intake blower automatically turns on when the "40-A solenoid" is energized.

ell reversal is a potentially damaging condition in fuel cells, as it is in conventional batteries, and may result from inadequate fuel being provided to a section of the fuel cell stack. During normal operation, twenty percent excess hydrogen is run through the stack to compensate for possible localized deficiencies in fuel distribution within the stack plates. If the hydrogen pressure drops below 45 psi, the fuel cell system will automatically shut down and indicate a "low fuel" condition.

To insure that the fuel cell is not loaded under a cell reversal condition, should one occur due to a failure in the fuel control system, a voltage imbalance sensing circuit was developed to continuously monitor the stack for a possible cell reversal. By comparing the voltages between adjacent 10-cell substacks, imbalances between substacks are detected. When the difference exceeds 0.6 V (an indication of reversal) the fuel cell is automatically shut down and disengaged from the load. A modification of this circuit can be used in a battery electric vehicle (by comparing each battery in the string) to detect a battery reversal and thereby reduce the possibility of a serious accident.

Fuel Cell Start-Up

When the stack temperature is within its operating range, the fuel cell turn-on sequence can be initiated after the stack intake and exhaust doors are opened to insure an adequate supply of oxygen and cooling air. The automatic turn-on sequence consists of turning on the intake air blower and then opening the hydrogen exhaust solenoid. This insures that the 50 psi line pressure is not inadvertently dropped across the stack due to solenoid timing, thus damaging the matrix. A three inches of water pressure relief valve is connected across the stack input and output to protect the stack from excessive pressures in the event that a solenoid fails to open or if there is any other restriction. After approximately one second, the intake and metering solenoids open for approximately four seconds to guarantee that the hydrogen electrodes are well supplied with hydrogen. The three metering valves and the fuel cell load contactor close to parallel the fuel cell with the battery. The fuel control system now becomes active since the stack will be supplying current to the auxiliary loads and will also be charging the batteries, if necessary.

Fuel Cell Shutdown

An automatic fuel cell shutdown sequence is initiated when either the ignition key is turned off or when a fuel cell condition such as excessive temperature or current, cell reversal, or loss of hydrogen is sensed. Such conditions might result in irreversible fuel cell degradation, should the load remain on the cell. The shutdown sequence begins by first opening the fuel cell contactor to remove the load from the stack. Then the intake and metering solenoids are closed. The intake blower continues to circulate air through the stack and the exhaust solenoid remains open for a short time to "purge" the stack of excess hydrogen. If the fuel cell system is going to remain off for any length of time, the intake and exhaust doors are manually closed. The closure of these doors and the intake and exhaust solenoids seals off the stack from the ambient air to minimize the take up of water by the phosphoric acid electrolyte during storage. When the shutdown is for fuel cell protective reasons, the batteries remain connected to the motor and the cart remains operable.

Throttle Compress Operation

There are occasions when a complete shutdown would not be necessary or desirable if relief could be given to the stressed subsystem by reducing the fuel cell load, thereby returning its operation to within its normal limits. A "throttle compress" circuit was designed that can monitor a number of variables within the system and then, in closed-loop fashion, compress the output of the speed control as these variables pass through unacceptable thresholds. Of particular interest in the fuel cell vehicle are fuel cell current and temperature. As the boundaries of normal operation are exceeded, the gain of the throttle is simply decreased until acceptable operating conditions are achieved. Thus, continued operation can be achieved under potentially marginal conditions, such as a long, steep hill on a hot day. The inputs to the throttle compress can be derived from any stress indicator in the system. In battery electric vehicles, motor and battery temperature and current can be incorporated in the loop.

Status

The golf cart has operated smoothly and reliably through the initial check-out tests. To date, the fuel cell system has been cycled from room to operating temperature approximately 40 times and driven for a total of 20 hours without any apparent performance degradation.

Because the fuel cell is in parallel with the batteries, the proportion of fuel cell current contributed to the motor load current is dependent upon the voltage vs current characteristics of each source in relation to the load requirements of the system.

The dual trace strip chart curves shown in Figure 9 were taken from the golf cart to show the relative contribution of fuel cell current to the total motor current demand. (The lower curve is slightly left justified to allow the recording pens to cross one another.) These curves clearly show that the fuel cell transient response for full throttle is quite good and that the fuel cell is charging the batteries when there is no motor load current demand. Notice how effectively load sharing is accomplished with a single diode control: under peak condition the current to the motor is over 300 A, but the fuel cell is only required to put out 50 A.

Reformer

The golf cart now carries hydrogen gas stored in aluminum scuba tanks. This represents a serious weight and volume penalty per energy stored. Methanol has a much better energy-to-weight ratio, being roughly half that of gasoline, and can be steam reformed to produce hydrogen and carbon dioxide according to the chemical equation

$$CH_3OH + H_2O \rightarrow 3H_2 + CO_2.$$

We will soon have the opportunity to work with a 2-kW reformer (Figure 10), through the courtesy of the U. S. Army MERADCOM, to develop an in-depth understanding of its operation and the variables that affect its performance. This reformer consists of a vaporizer, a super heater, and a reactor. A liquid mixture of 42% by weight methanol and 58% water (1:1.3 molar concentration) enters the reformer and is vaporized to a gas as it flows through the input tubes by extracting heat from the waste flue exhaust. Excess hydrogen fuel exiting the fuel cell is returned to the reformer and burned to super heat the methanol/water vapor to approximately 180° C. The super-heated fuel is then passed over a catalyst bed of stabilized zinc and copper oxides (United Catalyst G66B[illegible] or T-2130), which breaks down the methanol/water mixture to produce a moist fuel cell feed gas mixture of hydrogen and carbon dioxide.

Even though methanol reformation is not a new process, we are not aware of its being integrated into a vehicle. Therefore, as we gain experience with the reformer, we will be designing a fuel control system based on a methanol reformer fuel feed demand system rather than a stored hydrogen fuel feed.

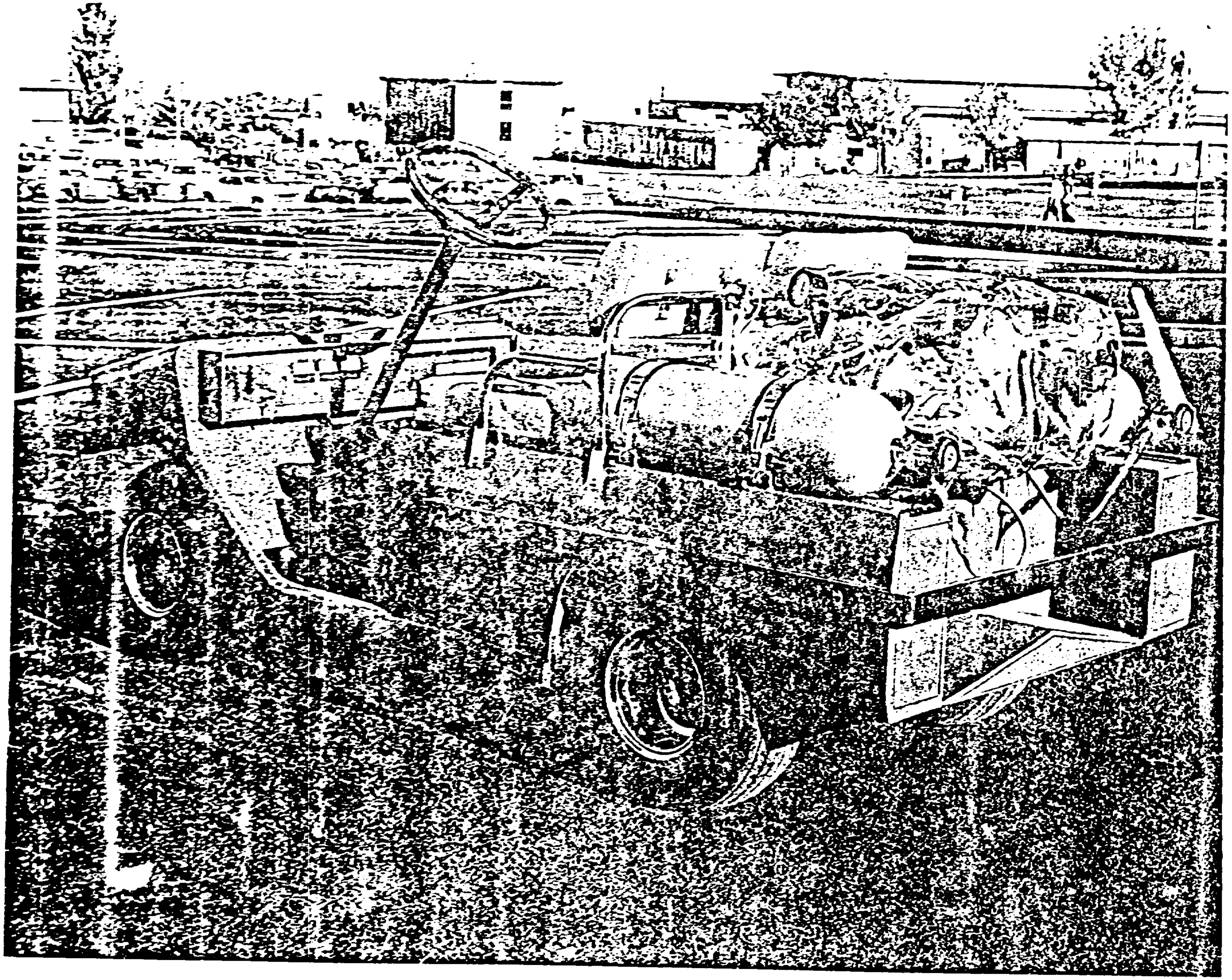


FIG. 1

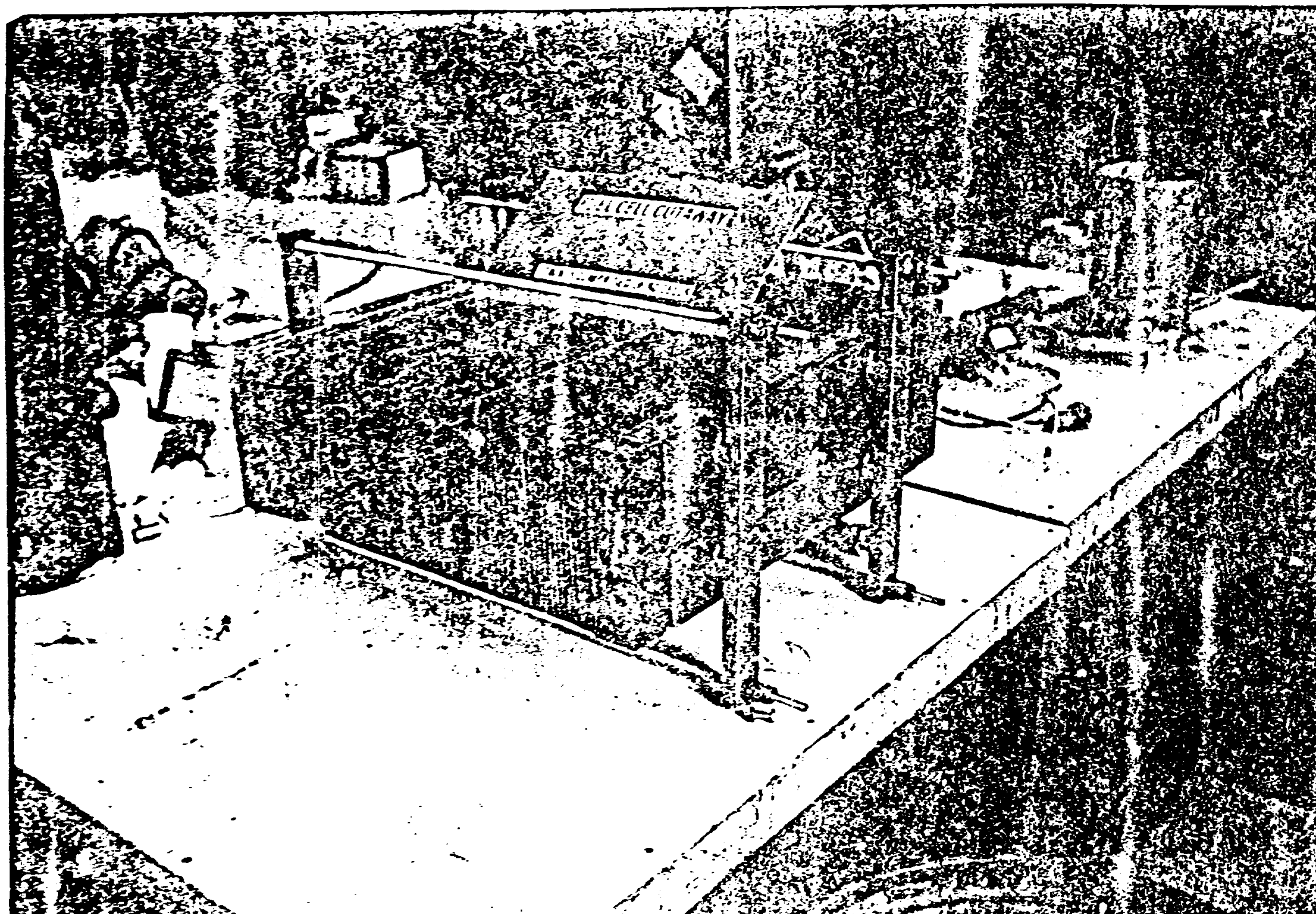


FIG.2

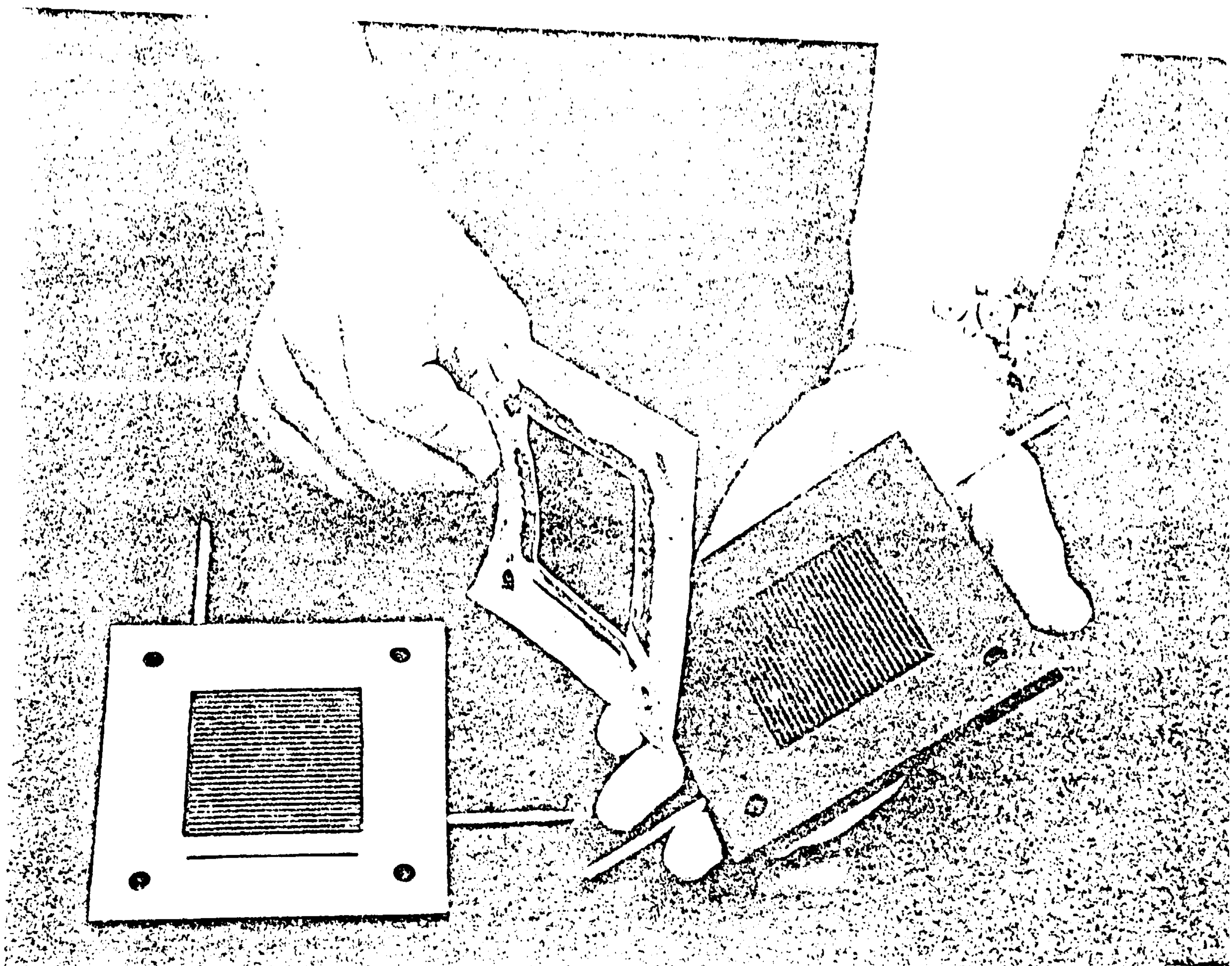


FIG.

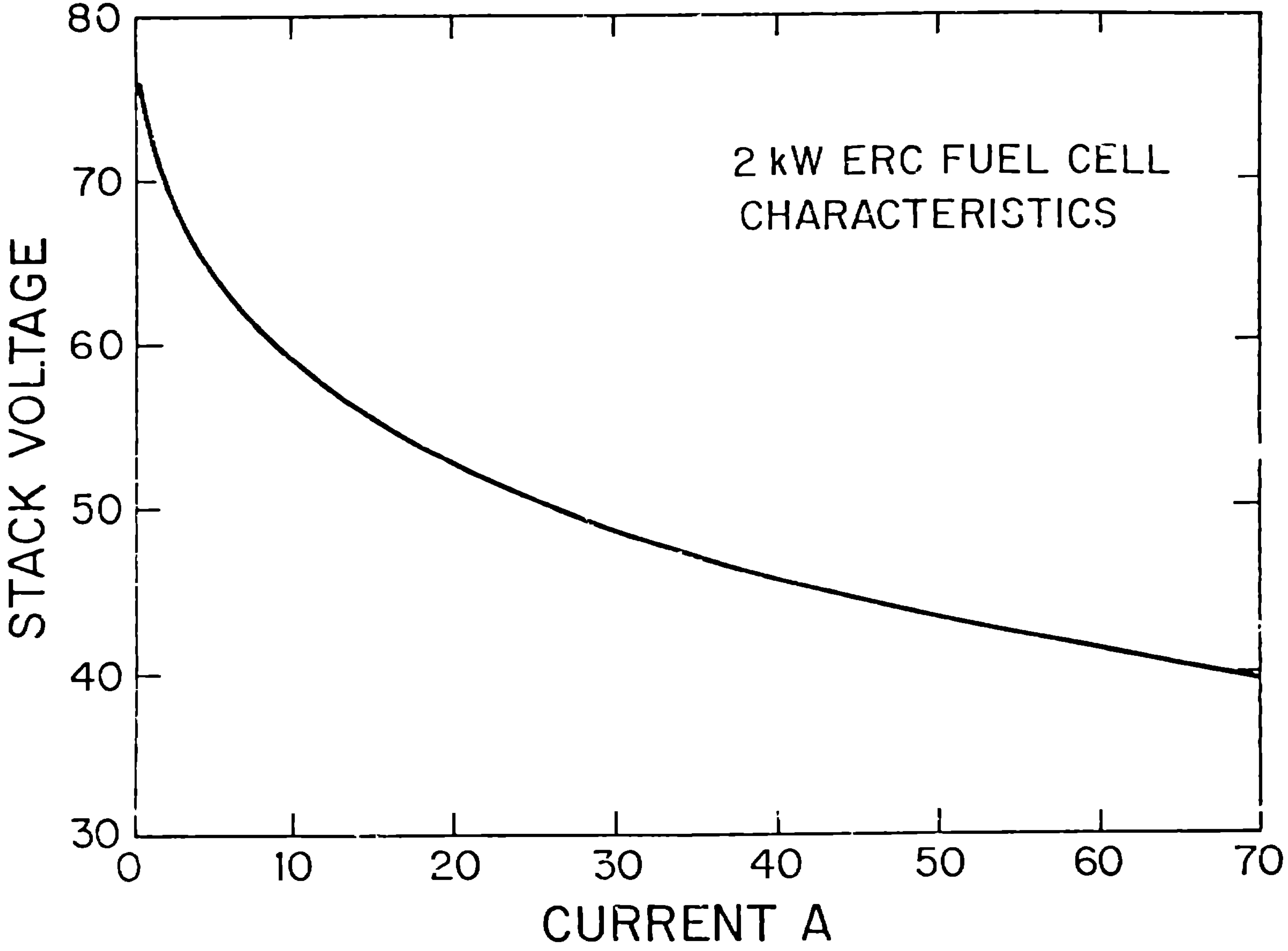

2 kW ERC FUEL CELL
CHARACTERISTICS
STACK VOLTAGE
CURRENT A
80
70
60
50
40
30
0
10
20
30
40
50
60
70

FIG.4

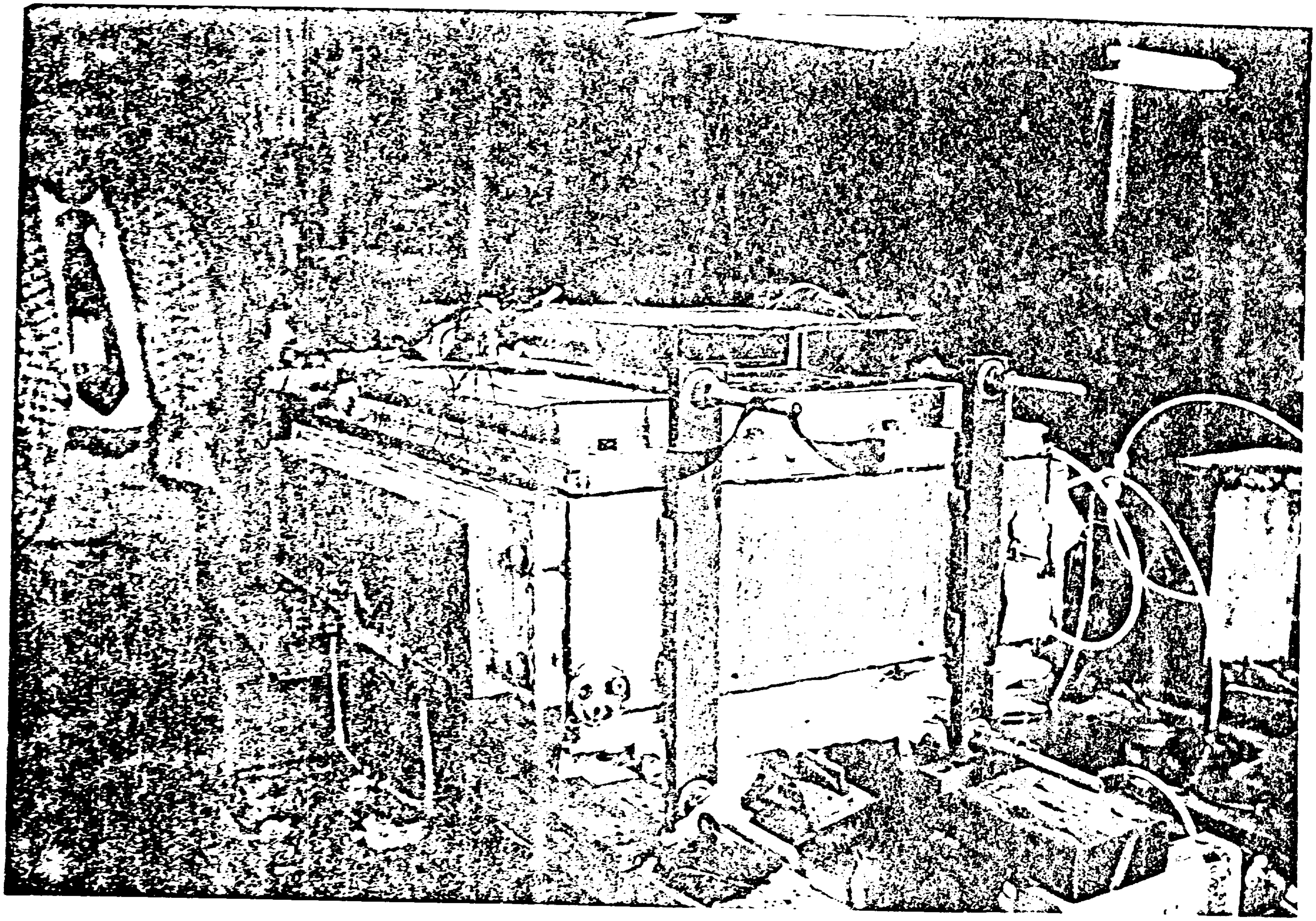


FIG.5

FUEL CELL POWERED ELECTRIC VEHICLE

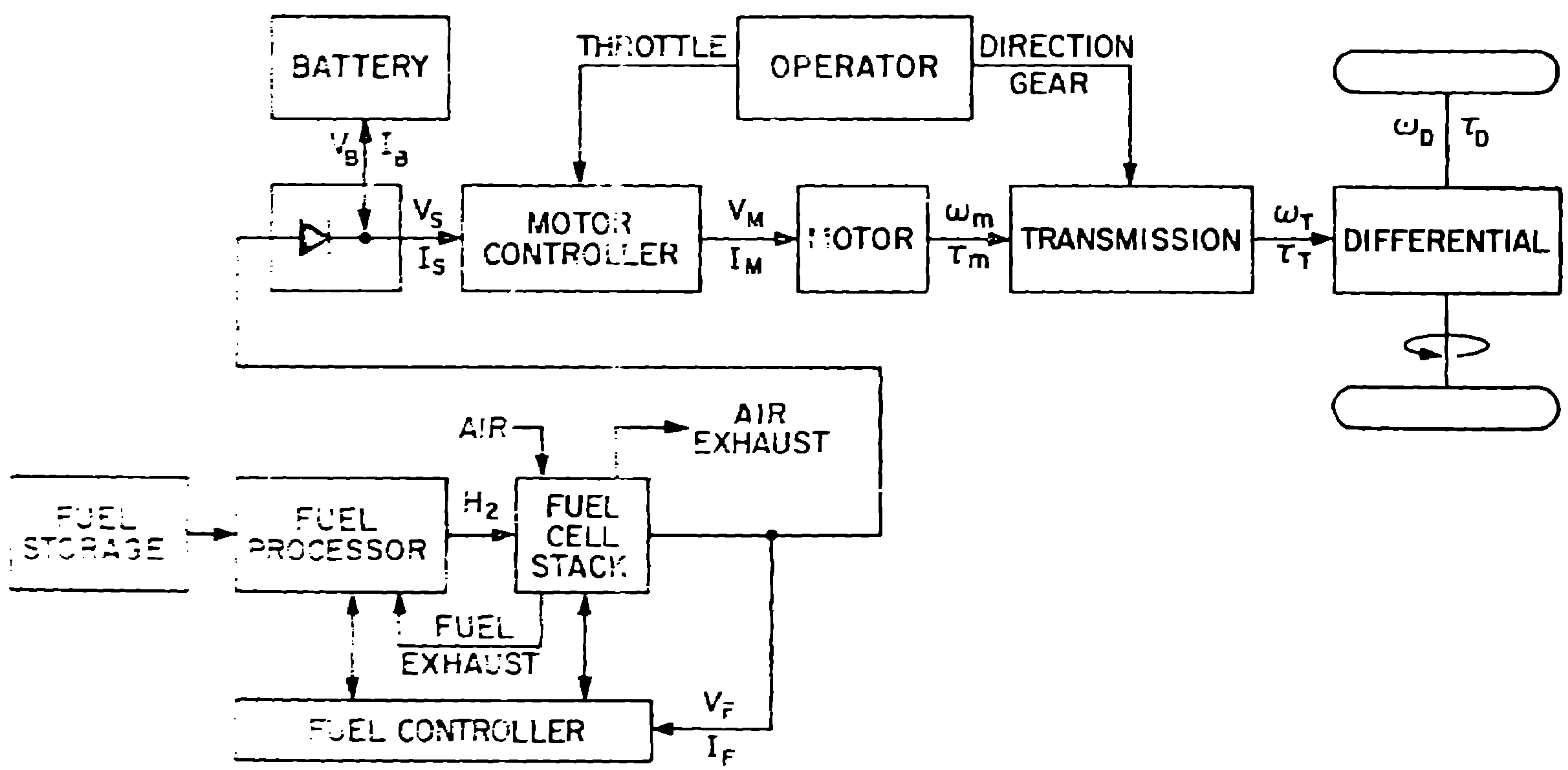
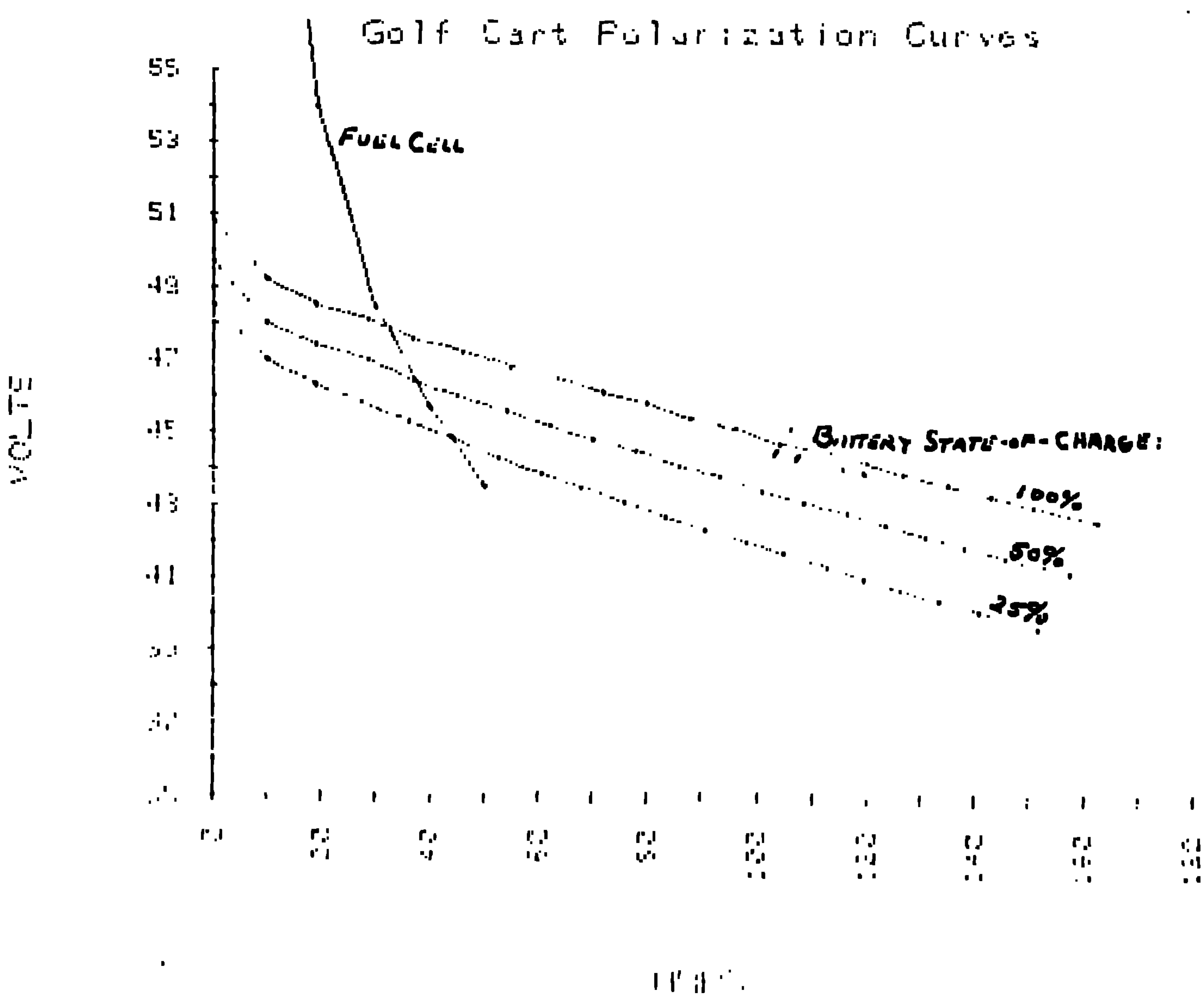


FIG.6



Golf Cart Polarization Curves
55
53
51
49
47
45
43
41
VOLTS
FUEL CELL
BATTERY STATE-OF-CHARGE:
100%
50%
25%

FIG. 7

FUEL CELL CONTROL BLOCK DIAGRAM

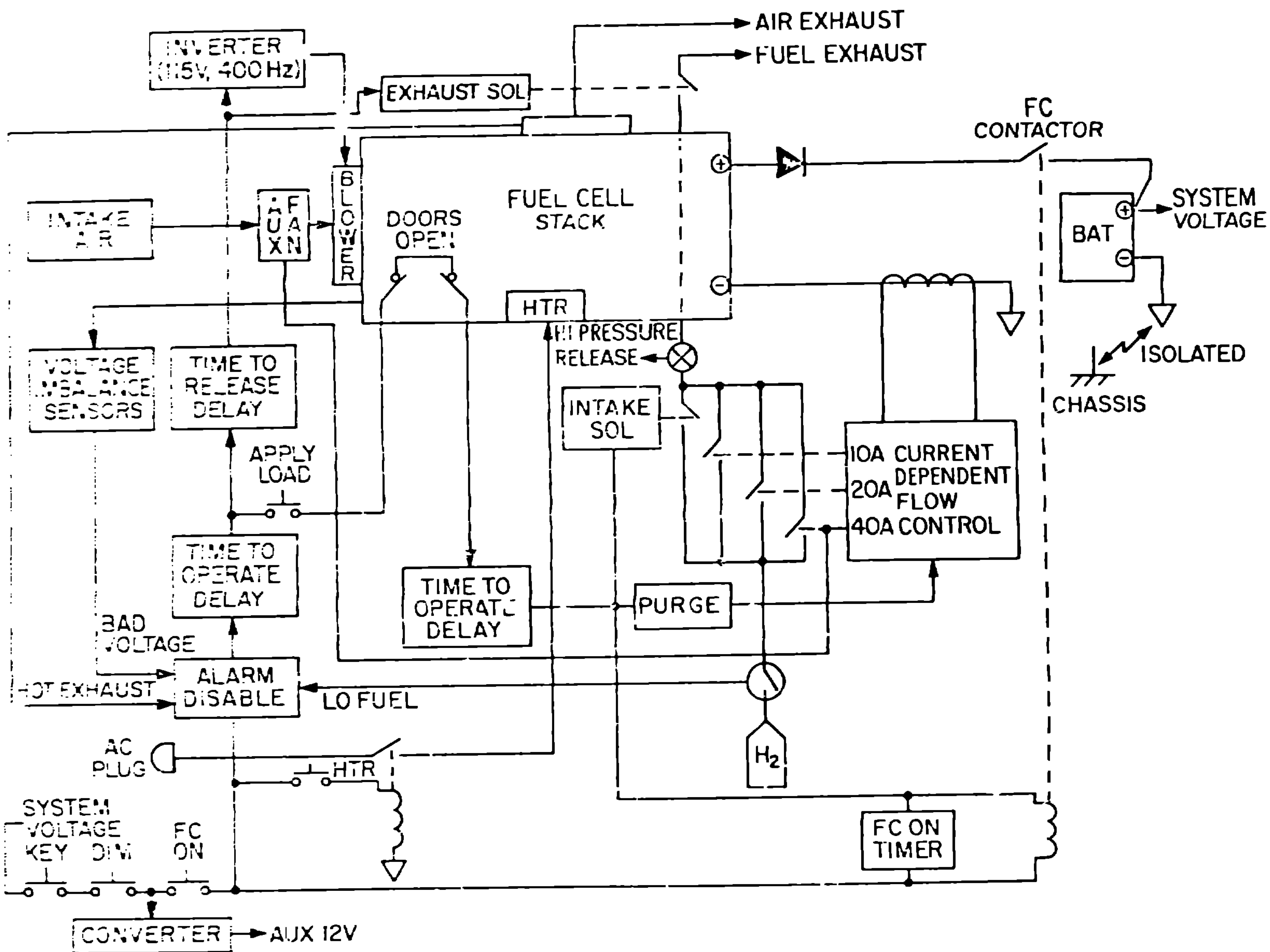


FIG.8

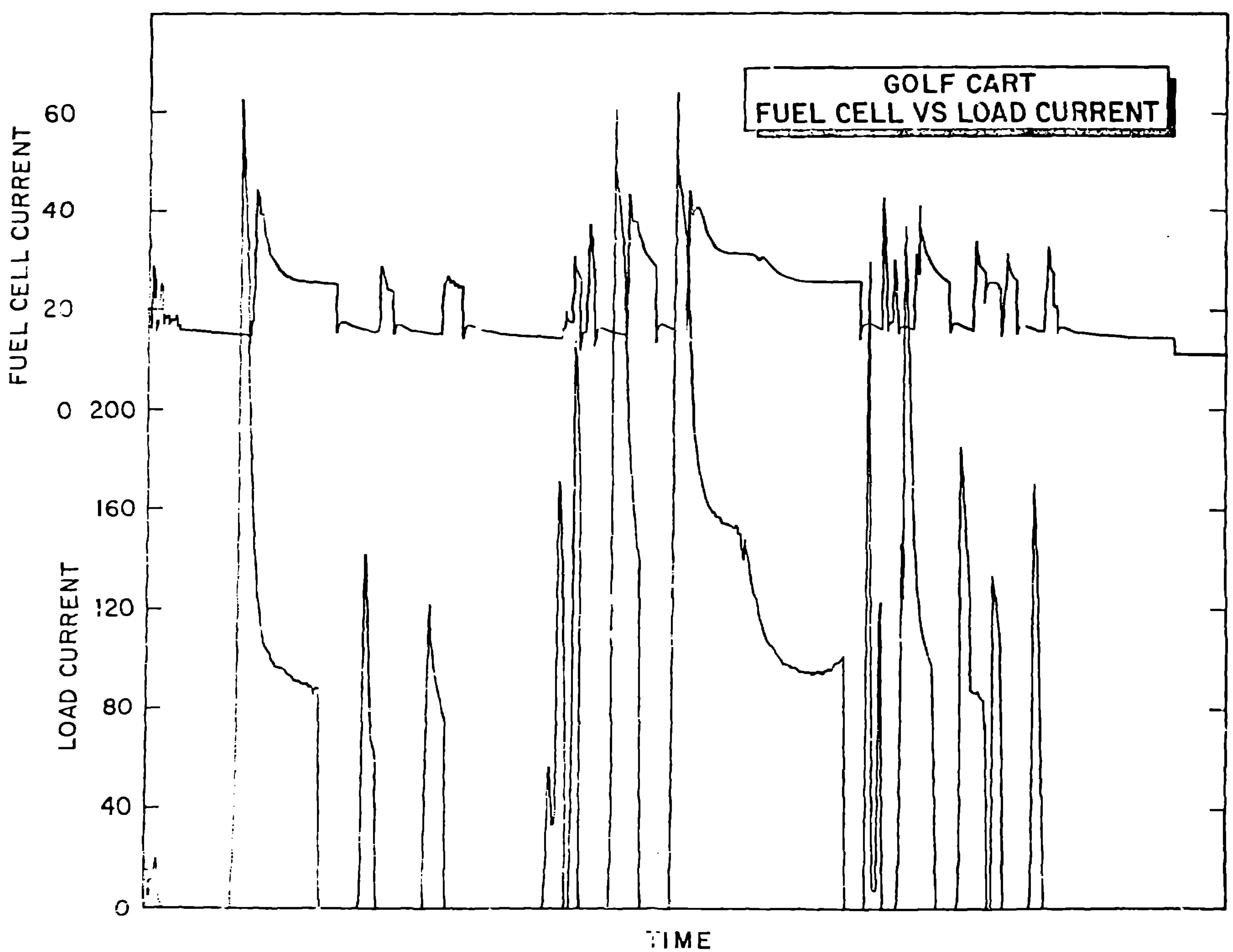

GOLF CART
FUEL CELL VS LOAD CURRENT
FUEL CELL CURRENT
60
40
20
0
200
160
120
80
40
0
LOAD CURRENT
TIME

FIG.9

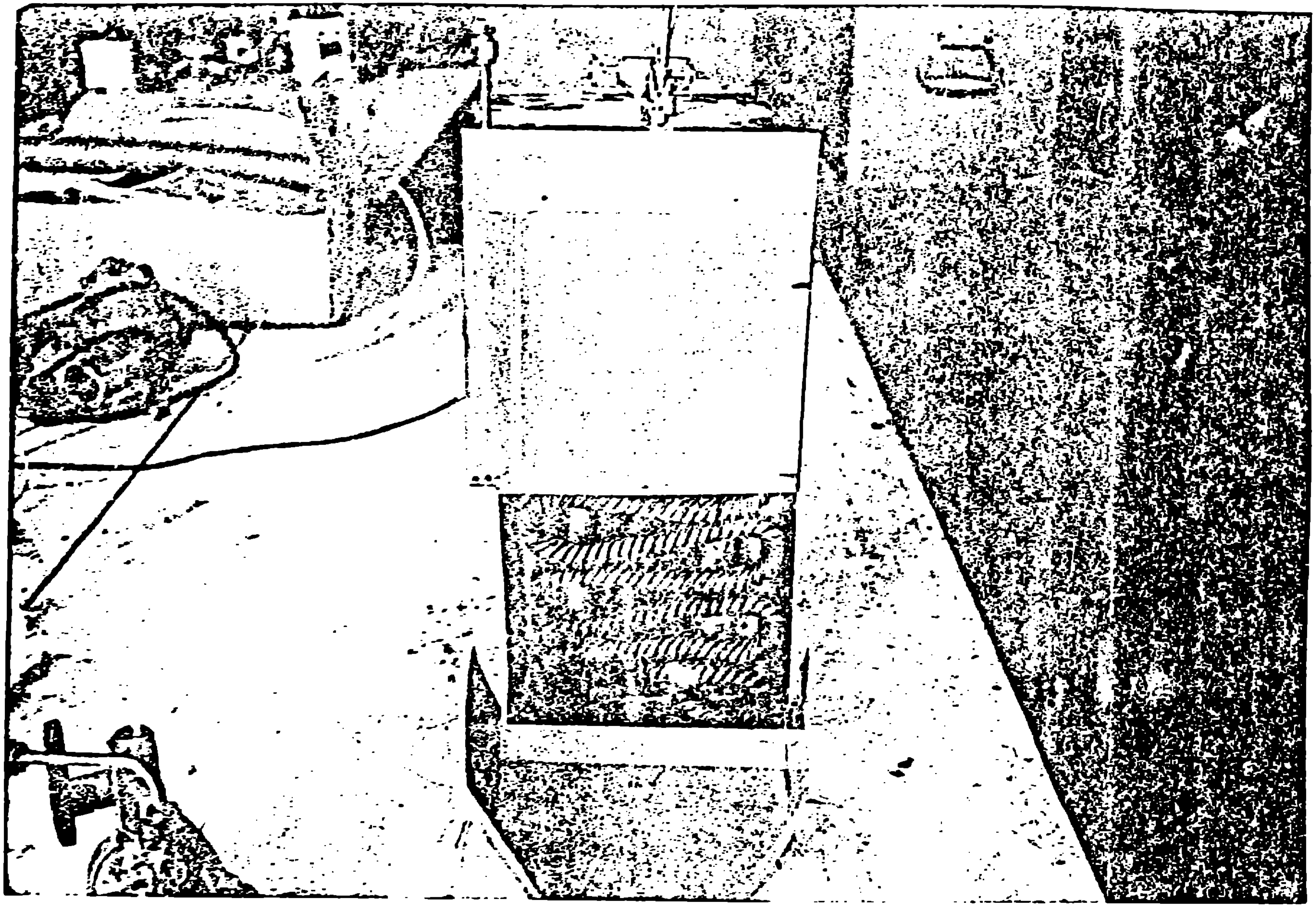


FIG.10